Action	Manuscript Number	Title	Authorship	Initial Date Submitted	Status Date	Current Status	Date Final Disposition Set	Final Disposition
View Submission	ARI_2017_1081	Detection System of Voids in Concrete based on Gamma Rays Scattering using GEANT4 Simulation Program	Other Author	Oct 23, 2017	Oct 30, 2017	Completed - Reject	Oct 30, 2017	Reject
View Submission Send E-mail	ARI_2018_907	Gamma backscattering analysis of flaw types and orientation based on Monte Carlo GEANT4 simulations	Corresponding Author	Nov 01, 2018	Oct 02, 2019	Completed - Accept	Oct 02, 2019	Accept
View Submission View Decision Letter Send E-mail	ARI-D-21-00507	Radiation shielding parameters analysis of Lombok pumice based on Monte Carlo GEANT4 simulations and XCOM	Corresponding Author	Jun 20, 2021	Jun 28, 2021	Completed - Reject	Jun 28, 2021	Reject

Rahadi Wirawan <rwirawan@unram.ac.id>

Invitation to revise manuscript ARI_2018_907

1 message

Richard Hugtenburg (Applied Radiation and Isotopes) <EviseSupport@elsevier.com> Tue, Mar 5, 2019 at 2:12 AM
Reply-To: r.p.hugtenburg@swansea.ac.uk
To: rwirawan@unram.ac.id

Ref: ARI_2018_907
Title: Gamma backscattering investigation of flaw type and orientation based on Monte Carlo GEANT4 simulation
Journal: Applied Radiation and Isotopes

Dear Dr. Wirawan,

Thank you for submitting your manuscript to Applied Radiation and Isotopes. We have completed the review of your manuscript. A summary is appended below. While revising the paper please consider the reviewers' comments carefully. We look forward to receiving your detailed response and your revised manuscript.

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- Log into EVISE® at: http://www.evise.com/evise/faces/pages/navigation/NavController.jspx?JRNL_ACR=ARI
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- Click on 'Agree to Revise'
- Make the required edits
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I look forward to receiving your revised manuscript as soon as possible.

Kind regards,

Richard Hugtenburg
Editor-in-Chief
Applied Radiation and Isotopes

Comments from the editors and reviewers:

-Reviewer 1
-Reviewer 1

In this paper, the investigation of a flaw presence effect in the material which modelled by a slit and its orientation in a duralumin (aluminum alloy) plate has conducted through a simulation of 137Cs gamma backscattering. The number of detecting photons will be obtained using GEANT4 based on the Monte Carlo simulation approach. Manuscript is well written and is in scope of ARI. I recommend to publish this paper after only English correction.

-Reviewer 2

The manuscript seems to be interesting but the English used to write it is presenting basic grammar errors making difficult to understand it. The complete text must to be corrected because at the moment it is complicated to understand the meaning of the sentences.

For example:

Page 1, line 29: it is written "Flaw is the most problems that found in the material " this part of the phase has no meaning. The authors are trying to write "flaw is the most common problem found in materials"?? I mean: the most what?? And the material defines a specific material? Or it is a generic observation considering different materials??

Page 1, line 30: continuing on the same phrase it is written "reducing the strength and an electrical properties of these material" it should be "reducing the strength and the electrical properties of those"?

This phrase should be something like that: "Flaw is the most common problem found in materials reducing its strength and its electrical properties" or something like that. This sentence has no meaning in the way it is written and it has grammatical errors. The authors must correct it, please.

Page 30: this sentence has no meaning " flaw characteristics such as a dimension, orientation and flaw type is an important which needed" ...Is it an important what??

The authors must to check the units, for example, grams per cubic centimeter is g/cm^3 and not gr/cm^3. The authors must, please, to check all units used in the manuscript. Part of the dimensions are in inches and part are in centimeters, the authors should write all them in the same unit system. This mix of units systems generates a confusion to the readers and makes difficult the understanding.

Did the authors simulate the Cs-137 source encapsulated or unencapsulated? Did the authors simulate the encapsulation of the source (if it is encapsulated)? The authors must to define the simulated spectra (with reference).

What is the detailed description of the detector in the simulation?? Did the authors simulate only the sensitive material or the window and the walls of the detector were simulated too? It needs to be clarified and this information must to be in the text.

The authors must to present the statistical fluctuation to each bin of the spectra .

The real differences among the spectra backscattering contribution for each slit shape must to be evaluated based on the statistical significance (at least use the chi-square test).

On the conclusion the authors affirm "Monte Carlo capability to show that gamma backscattering technique (GBT) can be applied"...However one may find several papers published showing that (follow the links to some papers):

https://indico.cern.ch/event/635057/contributions/2715896/contribution.pdf

https://inis.iaea.org/search/search.aspx?orig_q=RN:47081613
-Reviewer 1

https://www.worldscientific.com/doi/abs/10.1142/S2010194514601525

https://www.researchgate.net/profile/Lang_Trinh2/publication/309008222_Geant_4_Study_of_Concrete_Density_Measurement_Using_Gamma_Backscattering_Technique/links/57fda11808ae406ad1f3d532.pdf

https://link.springer.com/article/10.1007/s10967-017-5671-6

The authors must to define the innovation/novelty of the manuscript. So far it is not clear in the text.

Another important issue is that Geant4 has several physics lists and it can be personalized, so the authors must to define the transportation processes and models (specially the backscattering model(s)) evoked and its particularities such as the energy cut for secondary particles.

After the complete revision of the English and the main changes in the text the manuscript may be reviewed again properly.

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Rahadi Wirawan <rwirawan@unram.ac.id>

Received revision ARI_2018_907_R1

Applied Radiation and Isotopes <EviseSupport@elsevier.com> Fri, May 3, 2019 at 11:02 PM
Reply-To: ari.journal@elsevier.com
To: rwirawan@unram.ac.id

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Ref: ARI_2018_907_R1
Title: Gamma backscattering investigation of flaw type and orientation based on Monte Carlo GEANT4 simulation
Journal: Applied Radiation and Isotopes

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Received resubmission ARI_2018_907_R1

Applied Radiation and Isotopes <EviseSupport@elsevier.com> Wed, Jul 3, 2019 at 9:26 PM
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Title: Gamma backscattering investigation of flaw type and orientation based on Monte Carlo GEANT4 simulation
Journal: Applied Radiation and Isotopes

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Revision Requested - ARI_2018_907_R1 for Applied Radiation and Isotopes

Applied Radiation and Isotopes <EviseSupport@elsevier.com> Sun, Aug 11, 2019 at 11:56 AM
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Title: Gamma backscattering investigation of flaw type and orientation based on Monte Carlo GEANT4 simulation
Journal: Applied Radiation and Isotopes

Dear Dr. Wirawan,

On 12/Jul/2019 I sent the above-referenced request for your manuscript, and would kindly like to remind you to respond to this request by 10/Sep/2019.

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Rahadi Wirawan <rwirawan@unram.ac.id>

Revision Requested - ARI_2018_907_R1 for Applied Radiation and Isotopes

Applied Radiation and Isotopes <EviseSupport@elsevier.com> Tue, Sep 3, 2019 at 11:45 AM
Reply-To: ari.journal@elsevier.com
To: rwirawan@unram.ac.id

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Title: Gamma backscattering investigation of flaw type and orientation based on Monte Carlo GEANT4 simulation
Journal: Applied Radiation and Isotopes

Dear Dr. Wirawan,

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Rahadi Wirawan <rwirawan@unram.ac.id>

Received revision ARI_2018_907_R2

Applied Radiation and Isotopes <EviseSupport@elsevier.com> Sun, Sep 8, 2019 at 1:47 AM
Reply-To: ari.journal@elsevier.com
To: rwirawan@unram.ac.id

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Ref: ARI_2018_907_R2
Title: Gamma backscattering investigation of flaw type and orientation based on Monte Carlo GEANT4 simulation
Journal: Applied Radiation and Isotopes

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Rahadi Wirawan <rwirawan@unram.ac.id>

Received revision ARI_2018_907_R3

Applied Radiation and Isotopes <EviseSupport@elsevier.com> Sun, Sep 15, 2019 at 9:38 AM
Reply-To: ari.journal@elsevier.com
To: rwirawan@unram.ac.id

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Ref: ARI_2018_907_R3
Title: Gamma backscattering analysis of flaw types and orientation based on Monte Carlo GEANT4 simulations
Journal: Applied Radiation and Isotopes

Dear Dr. Wirawan,

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Manuscript Details

Manuscript number ARI_2018_907_R3

Title Gamma backscattering analysis of flaw types and orientation based on Monte Carlo GEANT4 simulations

Article type Full Length Article

Abstract

In this study, we modeled the effects of flaws in a solid material as three different slit types (rectangular, rectilinear, and semicircular) and their orientations in a duralumin (aluminum alloy) plate in simulations based on 137Cs gamma backscattering. The simulations were performed using the Monte Carlo GEANT4 simulation toolkit. The simulation results showed that the shape of the slit had a small effect on the backscattering peak curve. Rotating the slit on the Y-axis and Z-axis of the duralumin plate influenced the 137Cs backscattering peak height in the energy range from 0.185 to 0.20 MeV, where the backscattering peak areas exhibited specific patterns due to the slit orientations.

Keywords 137Cs source; duralumin; Monte Carlo simulation; orientation; slit.

Manuscript category Radiation Sources and Applications

Corresponding Author Rahadi Wirawan

Corresponding Author's Institution Universitas Mataram

Order of Authors Rahadi Wirawan, LiLy Maysari Angraini, Nurul Qomariyah, Abdul Waris, Mitra Djamal

Suggested reviewers Sajid Khan, Jakrapong Kaewkhao

Submission Files Included in this PDF

File Name [File Type]

Cover Letter_revision.docx [Cover Letter]

Comment Reviewer ARI Jurnal.docx [Response to Reviewers]

ARI_2018_907_highlights_edited_rev.doc [Highlights]

ARI_2018_907_manuscript_edited_rev.doc [Manuscript File]

Conflict of Interest.doc [Conflict of Interest]

To view all the submission files, including those not included in the PDF, click on the manuscript title on your EVISE Homepage, then click 'Download zip file'.

Research Data Related to this Submission

There are no linked research data sets for this submission. The following reason is given:
Data will be made available on request

Editor-in-Chief

International Journal Applied Radiation and Isotopes (ARI)

14th September 2019

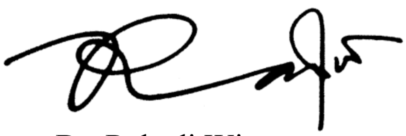
Dear Chief Editor,

Based on your email to revise the paper, we would like to submit the revision manuscript of our paper with the Title:

Gamma backscattering analysis of flaw types and orientation based on Monte Carlo GEANT4 simulation

(***R. Wirawan[1,*] , L. M. Angraini[1], N. Qomariyah[1], A. Waris[2], M. Djamal[2]***)

Sincerely,



Dr. Rahadi Wirawan
Department of Physics, FMIPA
University of Mataram
Jl. Majapahit 62 Mataram 83125
Indonesia

Reviewer 1

In this paper, the investigation of a flaw presence effect in the material which modelled by a slit and its orientation in a duralumin (aluminum alloy) plate has conducted through a simulation of 137Cs gamma backscattering. The number of detecting photons will be obtained using GEANT4 based on the Monte Carlo simulation approach. Manuscript is well written and is in scope of ARI. I recommend to publish this paper after only English correction.

Author comment: Thank you for your recommendation. I have made some corrections and hope the paper accomplishes the reviewer's criteria.

Reviewer 2

1. The manuscript seems to be interesting but the English used to write it is presenting basic grammar errors making difficult to understand it. The complete text must to be corrected because at the moment it is complicated to understand the meaning of the sentences.

   For example:

   Page 1, line 29: it is written “Flaw is the most problems that found in the material ” this part of the phase has no meaning. The authors are trying to write “flaw is the most common problem found in materials”?? I mean: the most what?? And the material defines a specific material? Or it is a generic observation considering different materials??

   Page 1, line 30: continuing on the same phrase it is written “reducing the strength and an electrical properties of these material” it should be “reducing the strength and the electrical properties of those"?

   This phrase should be something like that: “Flaw is the most common problem found in materials reducing its strength and its electrical properties” or something like that. This sentence has no meaning in the way it is written and it has grammatical errors. The authors must correct it, please.

   Page 30: this sentence has no meaning “ flaw characteristics such as a dimension, orientation and flaw type is an important which needed” ...Is it an important what??

   Author comment: Thank you for your review and suggestions. We have made several changes and rearrangements of the introduction. We hope that what is disclosed is in accordance with the reviewer's recommendations.

2. The authors must to check the units, for example, grams per cubic centimeter is g/cm^3 and not gr/cm^3. The authors must, please, to check all units used in the manuscript. Part of the dimensions are in inches and part are in centimeters, the authors should write all them in the same unit system. This mix of units systems generates a confusion to the readers and makes difficult the understanding.

Author comment: Thank you for your correction. We have made several corrections related to the unit system used (as shown in page 4-6)

3. Did the authors simulate the Cs-137 source encapsulated or unencapsulated? Did the authors simulate the encapsulation of the source (if it is encapsulated)? The authors must to define the simulated spectra (with reference).

Author comment: In the simulation, the source model (Fig. 1) is encapsulated with material and dimension we explain in page 5. **The gamma-ray source model considered in the simulation was an encapsulated point source comprising an acrylic (polymethyl methacrylate ($C_5H_8O_2$) with a density of 1.18 g/cm^3) disk model with a diameter of 2.5 cm and thickness of 0.5 cm.**

The energy spectrum distribution was shown in Fig. 6. (page 8) where the spectra not using line model but a marker point.

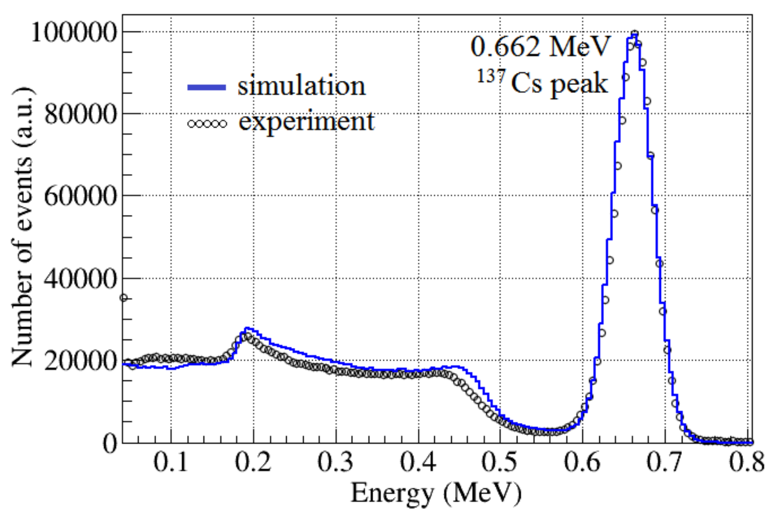


Fig. 6. Simulation and experimental energy spectrum distribution of ^{137}Cs gamma source.

4. What is the detailed description of the detector in the simulation?? Did the authors simulate only the sensitive material or the window and the walls of the detector were simulated too? It needs to be clarified and this information must to be in the text.

Author *comment*: *Thank you for the suggestion. We have added a description of the detector that we used in the simulation (page 4). The detector does not only consist of sensitive material but is surrounded by other layers i.e. MgO, SiO_2 and Al . Our detector model adopts the Shi et al. model (2002) but with a sensitive material size*

5.08 cm x 5.08 cm.

5. The authors must to present the statistical fluctuation to each bin of the spectra.

Author comment: The simulation result spectra (in histogram) were present in 300 bin channel of energy distribution. (snippet of the ROOT program that we use for smearing histogram of GEANT4 result)

```
//static TROOT rootBase("roothist","Histogram for G4 input");
osc =  new TFile("dataplat_pp861cm.root");
nt1 = (TNtuple*)gDirectory->Get("nt1");
//
int bin = 300;  //bin number to adjust with data
float emin = 0.0;
float emax = 1.5; //Maximum energy  to adjust with data
......
```

We do not clear about the statistical fluctuation to each bin of the spectra that reviewer mean. Whether the statistical fluctuation referred by the reviewer is the standard deviation (σ) ?. In general, this parameter is related to the FWHM and detector resolution (R) determined at the main peak or photopeak peak. For FWHM and resolution, we describe the tests of simulated detector models with experiments (Fig. 6 and in the page 8).

6. The real differences among the spectra backscattering contribution for each slit shape must to be evaluated based on the statistical significance (at least use the chi-square test).

Author comment: ***Thank you. Based on your suggestions we carry out statistical evaluations using a chi-square test. The results of our analysis are presented in Table 3 (page 17) and are described on page 11.***

7. On the conclusion the authors affirm "Monte Carlo capability to show that gamma backscattering technique (GBT) can be applied"...However one may find several papers published showing that (follow the links to some papers):
https://indico.cern.ch/event/635057/contributions/2715896/contribution.pdf
https://inis.iaea.org/search/search.aspx?orig_q=RN:47081613
https://www.worldscientific.com/doi/abs/10.1142/S2010194514601525
https://www.researchgate.net/profile/Lang_Trinh2/publication/309008222_Geant_4_Study_of_Concrete_Density_Measurement_Using_Gamma_Backscattering_Technique/links/57fda11808ae406ad1f3d532.pdf
https://link.springer.com/article/10.1007/s10967-017-5671-6

Author comment: ***Thank you for the review, we have made a revision related to the conclusions that have been written.***

Conclusions:

In this study, we conducted simulations to investigate the effects of the presence of different slit types and their orientation on the backscattered peak curve obtained with a ^{137}Cs gamma source. The shape of the slit had a small effect on the peak of the backscattering curve. In addition, rotation of the slit changed the peak heights and specific patterns were generated in the backscattering peak area curve.

8. The authors must to define the innovation/novelty of the manuscript. So far it is not clear in the text.

Author comment: ***The innovation/novelty of this research is observing the effects of shape and orientation of defects to the characteristics of the backscattering peak curve. This is written at the end of the third paragraph in the introduction.***

The shape and orientation of the flaws can potentially influence the scattering direction and scattering path of a photon when passing through a material. Studies are required in order to understand the significant characteristic of these effects on the backscattering peak curve and to develop a non-destructive testing system.

9. Another important issue is that Geant4 has several physics lists and it can be personalized, so the authors must to define the transportation processes and models (specially the backscattering model(s)) evoked and its particularities such as the energy cut for secondary particles.

Author comment: ***Thank you. We have written the physics lists of GEANT4 that involved in the simulation in the page 5. Physical processes used in this simulation is /physics/addPhysics empenelope and /physics/setCuts 0.01 mm is set for the production cuts of secondaries particle. The simulation is performed for 5.0 x 10^7 beamOns (histories).***

Highlights

- Geometry of duralumin plate affected ^{137}Cs backscattering peak curve.
- Slit type affected backscattering curve peak with ^{137}Cs gamma-rays.
- Flaw orientation influenced backscattering curve peak and area.
- GEANT4 used to simulate radiation measurements.

Gamma backscattering analysis of flaw types and orientation based on Monte Carlo GEANT4 simulations

R. Wirawan[1,*], L. M. Angraini[1], N. Qomariyah[1], A. Waris[2], M. Djamal[2]

[1]*Department of Physics, FMIPA, University of Mataram, Jl. Majapahit 62 Mataram 83125, Indonesia*

[2]*Department of Physics, FMIPA, Institut Teknologi Bandung, Jl. Ganesha 10 Bandung 40132, Indonesia*

Abstract

In this study, we modeled the effects of flaws in a solid material as three different slit types (rectangular, rectilinear, and semicircular) and their orientations in a duralumin (aluminum alloy) plate in simulations based on ^{137}Cs gamma backscattering. The simulations were performed using the Monte Carlo GEANT4 simulation toolkit. The simulation results showed that the shape of the slit had a small effect on the backscattering peak curve. Rotating the slit on the Y-axis and Z-axis of the duralumin plate influenced the ^{137}Cs backscattering peak height in the energy range from 0.185 to 0.20 MeV, where the backscattering peak areas exhibited specific patterns due to the slit orientations.

KEYWORDS: ^{137}Cs source, duralumin, Monte Carlo simulation, orientation, slit.

1. Introduction

Flaws are the most common problems that affect solid materials, where they can be both visible and invisible, and present in forms such as a density anomaly, cavity, crack or slit. The presence of flaws in materials can reduce the mechanical strength and affect their electrical properties. The gamma backscattering technique (GBT) can be employed to investigate invisible flaws located inside or on the back of high density materials. GBT is a non-destructive test based on the use of gamma penetrating radiation for determining the characteristics of test materials by analyzing the scattering energy spectra captured by the detector. Several studies have reported the use of GBT in application such as determining the local density perturbation (Boldo and Appoloni, 2014), concrete thickness (Almayahi, 2015), effective atomic number (Kiran et al., 2015; Sharma et al., 2017; Hosamani and Badiger, 2018), wood density (Tondon et al., 2017), and saturation depth (Nguyen et al., 2018).

* Corresponding author. E-mail: rwirawan@unram.ac.id

Computer simulations can be conducted in the early stages when studying the characteristics of flaws, which can be achieved using a Monte Carlo (MC) numerical simulation application. This type of simulation has been applied widely. Studies have shown that MC simulations can be employed successfully for the optimization of a detector collimator (Tavakoli-Anbaran et al., 2009), studying the performance of detectors (Peeples and Gardner, 2012), examining source distributions (Gurau and Sima, 2012), determining the concentrations of low-Z solutions (Priyada et al., 2012), evaluating voids in concrete (Priyada et al., 2013), investigating multiple backscattering on a target (Tarim et al., 2013), and improving the accuracy of a nuclear densitometer (Golgun et al., 2016). In addition, MC simulations have been conducted to determine the backscattered gamma energy distributions for metallic, biological, and shielding materials (Aydın, 2018).

During scattering interactions, the presence of flaws in a material will reduce the material's volume and also affect the number of electrons that might interact with a gamma photon, thereby influencing the characteristic backscattering curve detected for the energy spectrum distribution. In addition, the shape and orientation of the flaws can potentially influence the scattering direction and scattering path of a photon when passing through a material. Studies are required in order to understand the significant characteristic of these effects on the backscattering peak curve and to develop a non-destructive testing system.

In the present study, we investigated the effects on the gamma backscattering peak characteristics of different flaw types and their orientations located on the bottom of a duralumin (aluminum alloy) plate surface. This study was conducted using the GEANT4-MC simulation approach.

2. Theoretical background

The gamma photons detected when investigating the presence of flaws comprise the direct gamma-rays from a gamma source and indirect gamma-rays due to scattering by a plate, as shown in Fig. 1. The attenuation of gamma photons from the source to a detector is described using the Beer–Lambert formula:

$$I = I_s(E)\exp\left[-\sum\left(\frac{\mu(E)}{\rho}\right)_i \rho_i r_i\right], \qquad (1)$$

where $I_s(E)$ is the intensity of the gamma source, ρ is the density of the plate material, $\left(\frac{\mu(E)}{\rho}\right)$ is the mass absorption coefficient, and r is the photon movement path.

According to the single scattering model (Ball et al., 1998), photons undergo attenuation before interacting with matter. They are then scattered by the scattering matrix volume and attenuated when the photon moves toward the detector. This scattering involves electron–electron interactions via the Compton scattering mechanism. The number of electrons can be determined based on the electron density n in the following relationship:

$$n = Z\frac{N_A \rho}{A}, \tag{2}$$

where Z is the atomic number, N_A is Avogadro's number, ρ is the density of the material, and A is the atomic mass. Photons will be deflected at a certain angle and scattering energy. The distribution of scattered photons is described by the differential cross-section per solid angle ($d\sigma/d\Omega$) with the Klein–Nishina formula (Knoll, 1989):

$$\frac{d\sigma}{d\Omega} = \frac{Zr_0^{\,2}}{2}\left(1+\cos^2\theta\right)\left(\frac{1}{1+\alpha(1-\cos\theta)}\right)^2\left(1+\frac{\alpha^2(1-\cos\theta)^2}{(1+\alpha(1-\cos\theta))\left(1+\cos^2\theta\right)}\right), \tag{3}$$

where $\alpha = E/m_0c^2$, r_0 is the classical electron radius (2.82 fm), and θ is the scattered photon angle.

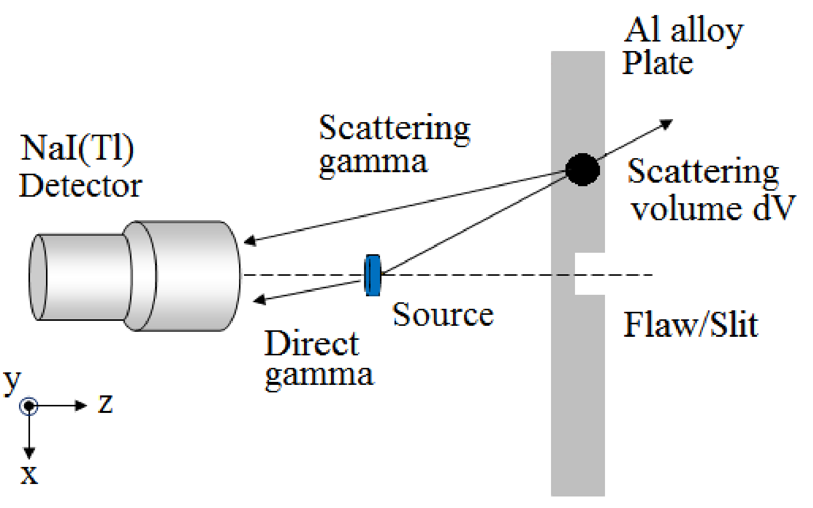


Fig. 1. Geometrical setup of the gamma interaction simulation.

The scattering intensity of a detected gamma photon can be obtained using equation (4):

$$I_{scatt} = \int I_s(E)\exp\left[-\sum\left(\frac{\mu(E)}{\rho}\right)_i \rho_i r_i\right] x \left(Z\frac{N_A\rho}{A}\right) x \left(\frac{d\sigma}{d\Omega}\right) d\Omega\, dV, \tag{4}$$

where dV is the scattering volume element of the plate, $d\Omega$ is the solid angle, and $I_s(E)$ is the source intensity. The total intensity detected by the detector comprises the direct intensity from the source and the indirect intensity from scattering interactions, as summarized in equation (5).

$$I = I_s(E)\exp\left[-\sum\left(\frac{\mu(E)}{\rho}\right)_i \rho_i r_i\right] + \int I_s(E)\exp\left[-\sum\left(\frac{\mu(E)}{\rho}\right)_i \rho_i r_i\right] x \left(Z\frac{N_A \rho}{A}\right) x \left(\frac{d\sigma}{d\Omega}\right) d\Omega\, dV, \qquad (5)$$

The volume element parameter can influence the scattered photon intensities detected by a detector. Therefore, reducing the volume element from the solid material (plate) will affect the intensity of the detected photons. In this study, the number of photons detected was traced using the MC GEANT4 simulation approach in the form of an energy distribution spectrum curve.

3. GEANT4 simulation

In order to obtain gamma-ray scattering intensity data, the simulation was conducted using the GEANT4 (GEometry ANd Tracking) MC simulation toolkit, which is an object-oriented program (Agostinelli et al., 2003). A schematic showing the design of the backscattering gamma simulation is depicted in Fig. 2. The duralumin (aluminum alloy) plate material comprised Al = 94.55%, Cu = 4.36%, and Mg = 1.09% according to energy-dispersive X-ray spectroscopy analysis (Wirawan et al., 2017) and using the density formulation for a mixed material given in equation (6):

$$\rho_{Al\,alloy} = \frac{\rho_{Mg}V_{Mg} + \rho_{Al}V_{Al} + \rho_{Cu}V_{Cu}}{V_{Mg} + V_{Al} + V_{Cu}}, \qquad (6)$$

where the density (ρ) value was about 2.77 g/cm^3. As shown in Fig. 2, a duralumin plate (dimensions: 8.0 cm × 6.0 cm × 1.0 cm) and ^{137}Cs gamma source were placed 4.3 cm and 1.55 cm from the detector's surface, respectively. The detector model used in the simulation was a scintillation detector with cylindrical NaI(Tl) measuring 5.08 cm × 5.08 cm as the sensitive material. According to the model of Shi et al. (Shi et al., 2002), the NaI(Tl) was covered by MgO, SiO_2, and Al layers with thicknesses of 0.185 cm, 0.3 cm, and 0.05 cm, respectively.

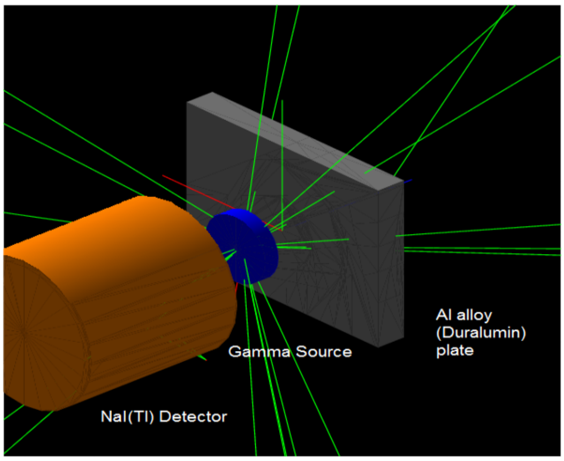


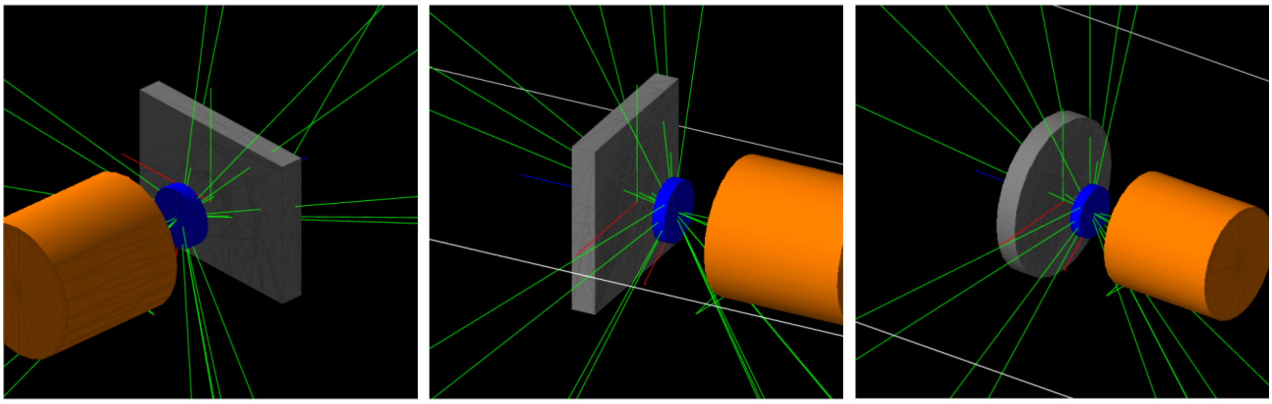
Fig. 2. GEANT4 visualization simulation setup for detecting backscattering gamma-rays from a duralumin (aluminum alloy) plate.

The gamma-ray source model considered in the simulation was an encapsulated point source comprising an acrylic (polymethyl methacrylate ($C_5H_8O_2$) with a density of 1.18 g/cm^3) disk model with a diameter of 2.5 cm and thickness of 0.5 cm. The physical processes used in the simulation was "/physics/addPhysics empenelope" and "/physics/setCuts 0.01 mm" was set for producing cuts of secondary particles. The simulation was performed for 5.0×10^7 beamOns (histories).

The smearing process was performed for the histogram output obtained from GEANT4 in order to create a spectrum curve for the energy distribution in 300 bins. The energy resolution of the NaI(Tl) detector used for smearing was 8.6%. The backscattering peaks of the gamma-rays were analyzed based on a Gaussian function and Chi-square method for the fitted settings. The smearing process and analysis was conducted using the ROOT C / C ++ program.

Construction of plate and flaw geometry

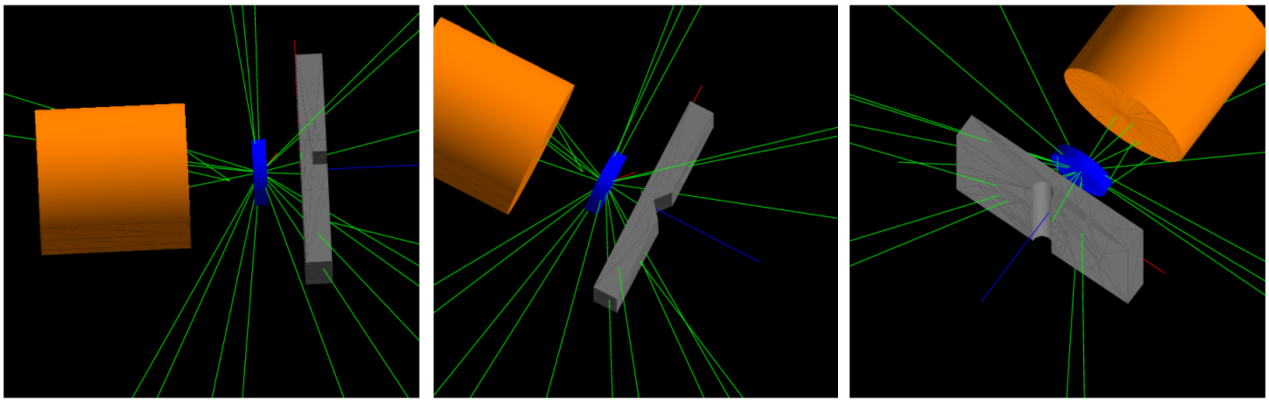
In order to study the influence of the geometry of the plate, we simulated three types of plates with the same volume (Fig. 3), i.e., rectangular (dimensions: 8.0 cm × 6.0 cm × 1.0 cm), rectilinear (6.93 cm × 6.93 cm × 1.0 cm), and a disk (radius = 3.91 cm radius and thickness = 1 cm).



(a) (b) (c)

Fig. 3. Visualizations of the geometry for the three types of plates using GEANT4: (a) rectangular, (b) rectilinear, and (c) disk.

In order to determine the effect of the presence of a flaw/slit on the gamma backscattering spectrum, we simulated the presence of three types of slit on the bottom of the duralumin plate, as shown in Fig. 4. The slit types were rectangular (0.6 cm × 6.0 cm × 0.5 cm), triangular (1.2 cm × 6.0 cm × 0.5 cm), and semicircular (radius = 0.437 cm and height = 6.0 cm), and they all had the same volume.

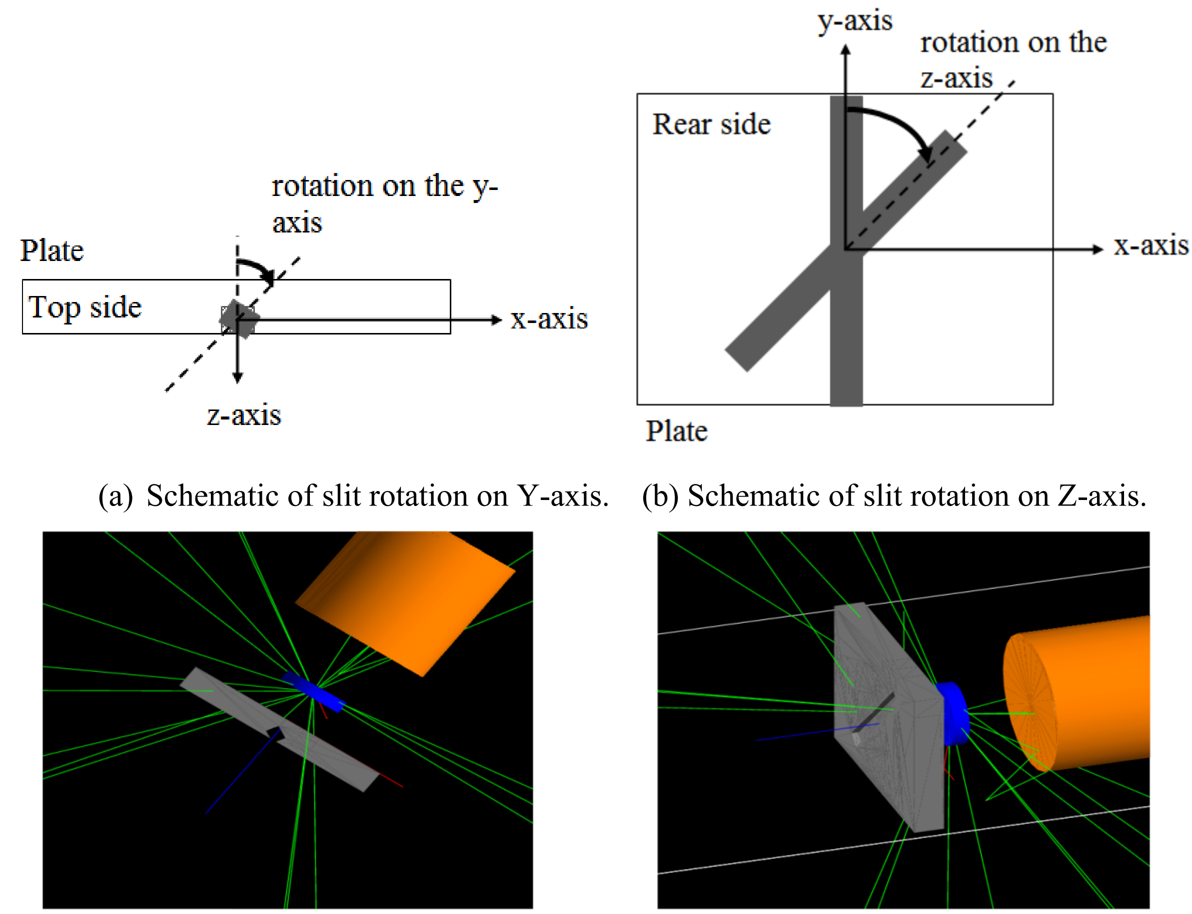


(a) Rectangular slit (b) Triangular slit (c) Semicircular slit

Fig. 4. Visualizations of different types of slit with GEANT4.

Construction of slit orientation

Furthermore, in order to study the characteristics of the backscattering peak for ^{137}Cs gamma depending on the slit orientation, we simulated slit orientations perpendicular (Y-axis) and parallel to the normal plate surface (Z-axis), as depicted in Fig. 5. The slit type considered in this study was rectangular with dimensions of 0.6 cm × 6.0 cm × 0.5 cm.



(a) Schematic of slit rotation on Y-axis. (b) Schematic of slit rotation on Z-axis.

(c) GEANT4 visualization of rotation on Y-axis. (d) GEANT4 visualization of rotation on Z-axis.

Fig. 5. Different slit orientations.

Due to the presence of a slit/crack and its orientation, the backscattering peak was analyzed, i.e., the peak curve height and peak area of the backscattering curve. The backscattering peak height was determined based on a Gaussian fitted curve and the characteristics of the Gaussian curve. In addition, the area (A) below the peak was determined using the following formula (Knoll, 1989).

$$A = \sqrt{2\pi}\,\sigma\, y_0 = 2.507\sigma\, y_0, \quad (8)$$

The full-width at half maximum (*FWHM*) was evaluated using the following formula:

$$FWHM = 2\sqrt{2\ln 2}\,\sigma = 2.355\sigma, \quad (9)$$

where y_o is the maximum height of the curve's peak and σ is the standard deviation. The resolution (R) of the *FWHM* can be determined using the following equation:

$$R(\%) = \frac{FWHM}{H_0} \times 100, \quad (10)$$

where H_o is the centroid of the curve's peak.

A Chi-square test was performed to determine the significance of the differences in the gamma backscattering peaks for the three types of modeled slit.

4. Results and discussion

The simulation approach for experimental testing was conducted after testing the detector's performance, including the detector's response function to the radiation from a source. Figure 6 shows a graph of the source energy spectrum obtained from the ^{137}Cs gamma source simulation results and the source radiation measurements for the 5-μCi source's activity for 5 min. The upscaling ratio used for the simulation was about 1.23. Based on the Gaussian curve fitting results for the main peak (0.662 MeV), the *FWHM* value for the simulation was 0.05857 and the resolution (*R*) was 8.8565%. In addition, the *FWHM* value for the experimental curve was 0.057425 with a resolution (*R*) of 8.6801%.

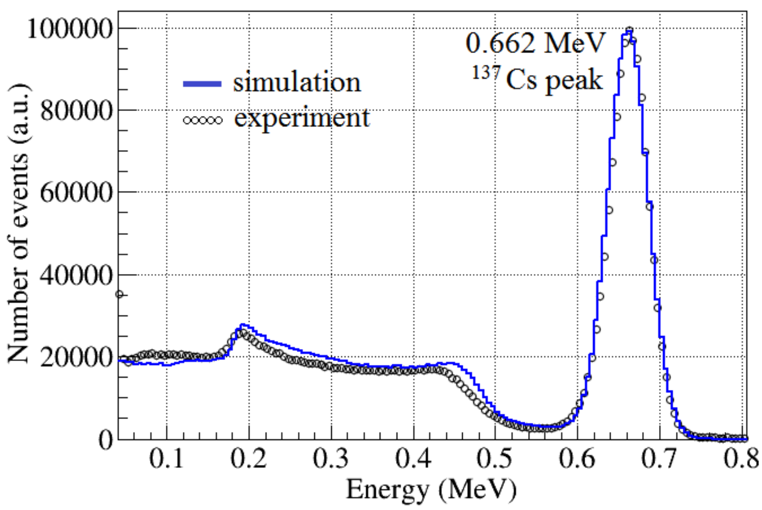
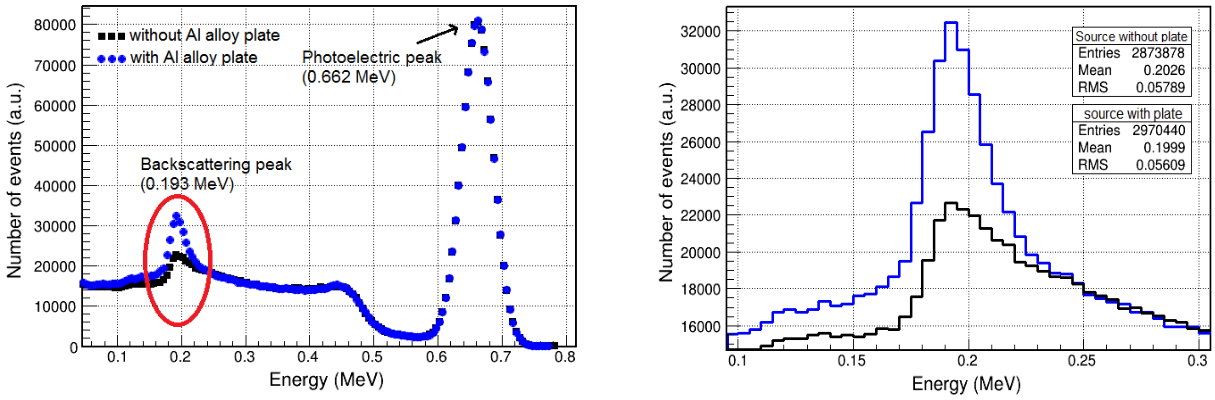


Fig. 6. Simulated and experimental energy spectrum distributions for the ^{137}Cs gamma source.

According to the resolution of the main peak, the difference in resolution between the simulated and experimental values was about 2.03%. These results indicate that the detector model designed for obtaining measurements could produce an energy distribution curve similar to that obtained in experiments.

The effect of the presence of the duralumin plate in front of the ^{137}Cs gamma source was assessed based on the increase in the height of the backscattering peak in the gamma-ray scattering spectrum, as shown in Fig. 7a. After 5.0×10^7 beamOns from the gamma photon source, the photon number that entered the scintillation detector was about 2873878 (5.75%) in the absence of the duralumin plate.



(a) Energy spectrum distribution (b) Backscattering peak

Fig. 7. Energy spectrum distribution for the ^{137}Cs gamma source with and without the Al alloy plate.

However, when the duralumin plate was present, the photon number increased by 0.19% to 2970440 (5.94%), as shown in Fig. 7a. These additional photons were due to photons interacting with electrons in the aluminum alloy, which led to their deflection and attenuation when they moved toward the detector. The photon intensity contributed to the increase in the backscattering peak curve in the gamma energy spectrum distribution, as depicted in Fig. 7b. The change in the height of the backscattering peak due to the presence of the plate had the same pattern as that obtained experimentally by Sharma et al. (2017) when determining the effective atomic number using a ^{22}Na gamma source.

Moreover, the plate geometry influenced the backscattering peak in the energy spectrum for gamma scattering. Simulations of the different types of plates showed that the numbers of photons entering the detector when the plate comprised a rectangular block, rectilinear block, and disk were 2970440 (5.940%), 2970607 (5.941%), and 2969772 (5.939%), respectively. According to these results, the plate type influenced the number of photon entries. The heights of the backscattering peaks are shown in Fig. 8.

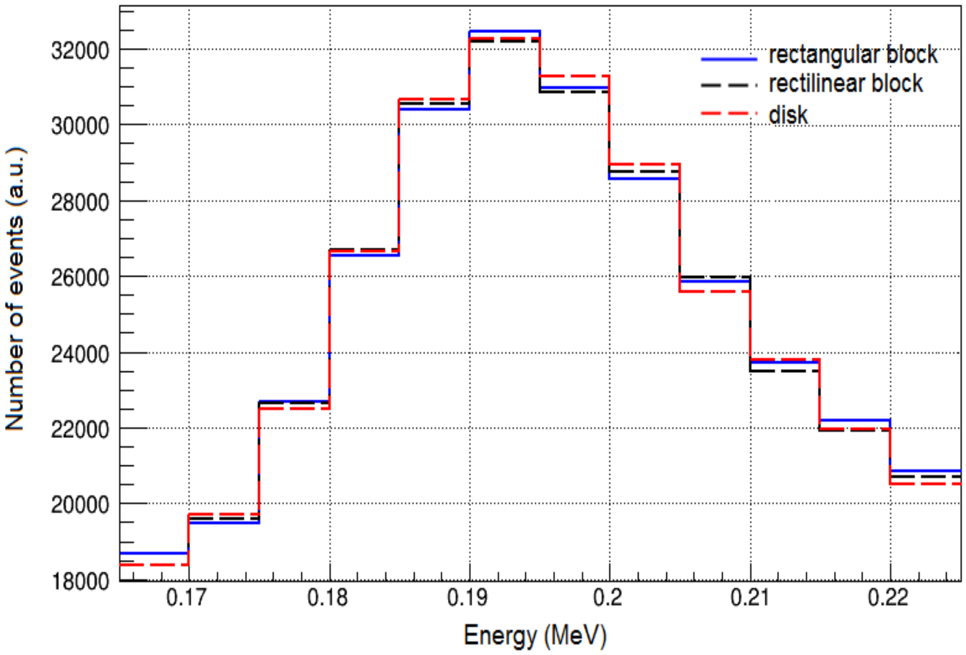


Fig. 8. Backscattering peak curves obtained for ^{137}Cs gamma-rays.

According to the Gaussian curves fitted for the backscattering peaks (as shown in Table 1), the rectangular block plate type obtained a higher curve height than the other two plate types. The ratios of the backscattering peak height relative to the number of photon entries were 1.092%, 1.086%, and 1.084% for the rectangular block, rectilinear block, and disk, respectively. The scattering interactions and attenuation of photons throughout the material accounted for the differences in the backscattering peak heights.

The presence of a slit under the duralumin plates influenced the backscattering peak in the gamma energy distribution for the ^{137}Cs source. Figure 9 show the backscattering peaks obtained for a plate without a slit and plates with the three different types of slits presented in Fig. 4. The different slit types yielded different numbers of photon entries. The slits had the same volume but the shape of each slit affected the number of photons that entered the detector. The presence of a slit reduced the height of the backscattering peak compared with that in the absence of a slit. The decrease in the backscattering peak for the ^{137}Cs gamma-ray scattering was due to the reduced volume of the scattering plate (or slit volume). Thus, there was a decrease in the number of electrons that probably interacted with gamma photons from the ^{137}Cs source. The reduced volumes also affected the attenuation of the scattered photon intensity when photons passed through the duralumin plate.

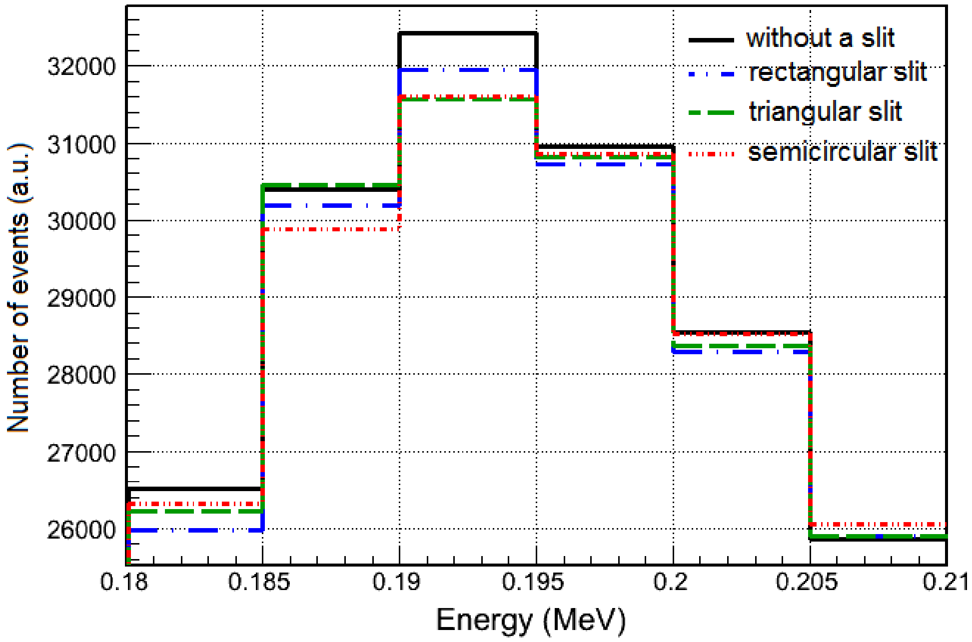


Fig. 9. Backscattering peaks obtained using the plate without and with a slit.

The Gaussian curves fitted to the gamma backscattering peaks obtained for the three slit types showed that the rectangular slit yielded the highest peak, followed by the semicircular slit and the triangular slit (Table 2). The backscattering peak heights for each type of slit were 31950.2 (1.077% of the photons detected) with the rectangular slit, 31504.2 (1.062%) with the triangular slit, and 31593.2 (1.065%) with the semicircular slit. The significances of the differences in the backscattering peaks were evaluated using the Chi-square test based on the histogram height. The Chi-square test over the histogram energy range between 0.18 and 0.21 MeV (see Table 3) generated a critical value of 12.137 with 10 degrees of freedom and a confidence level of 72% (the critical value for the 95% confidence level was about 18.307). Thus, the slit shape had a small effect on the gamma backscattering peak curve in the energy distribution spectrum but the peaks were not significantly different from each other.

Moreover, the rotation of the slit influenced the backscattering peaks for the ^{137}Cs gamma-ray scattering energy received by the detector. This effect was demonstrated by the different heights of the backscattering peak due to the rotation of the slit on the Y-axis, as shown in Fig. 10 and Fig. 11.

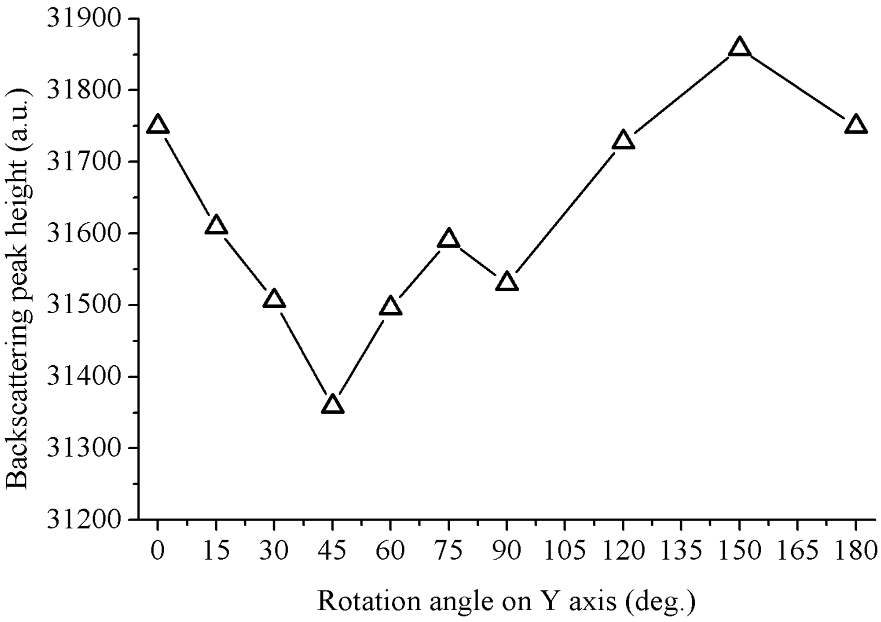


Fig. 10. Heights of [137]Cs gamma backscattering peaks with different rotational angles on the Y-axis for a rectangular plate of duralumin (aluminum alloy).

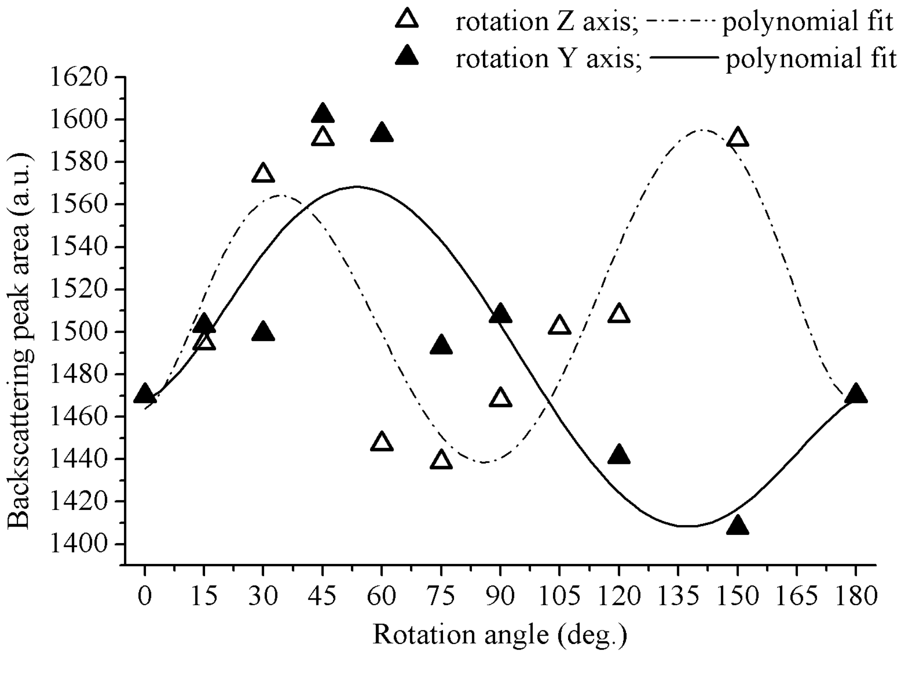


Fig. 11. Areas of the [137]Cs backscattering peaks with different rotations of the slit for the rectangular plate.

According to the backscattering peak areas shown in Fig. 11, the effect of rotating the slit on the Y-axis can be described by the polynomial: $Y_{Y\_RECTA} = -3.87E\text{-}08x^5 + 1.8E\text{-}05x^4 -$

$0.002x^3 + 0.122x^2 + 0.597x + 1468$. In addition, the effect of rotating the slit on the Z-axis can be described by the polynomial: $Y_{Z\_RECTA} = 1.6E\text{-}09x^6 - 8.5E\text{-}07x^5 + 1.6E\text{-}04x^4 - 0.012x^3 + 0.339x^2 + 0.739x + 1464$. The coefficients of determination (R^2) for the fitted curves were about 0.800 and 0.753 for rotation on the Y-axis and Z-axis, respectively. These results indicate that rotating the slit affected the energy spectrum distribution detected for the gamma scattering, especially in the backscattering peak area.

The influence of the slit orientation was also investigated when the slit was rotated on the Z-axis or the axis perpendicular to the surface plane of the duralumin plate. Simulations were performed for rectangular plates and rectilinear plates with the same volume and same slit size. Figure 12 shows that the slit orientation significantly affected the height of the backscattering peak in the spectrum of the gamma energy distribution for ^{137}Cs.

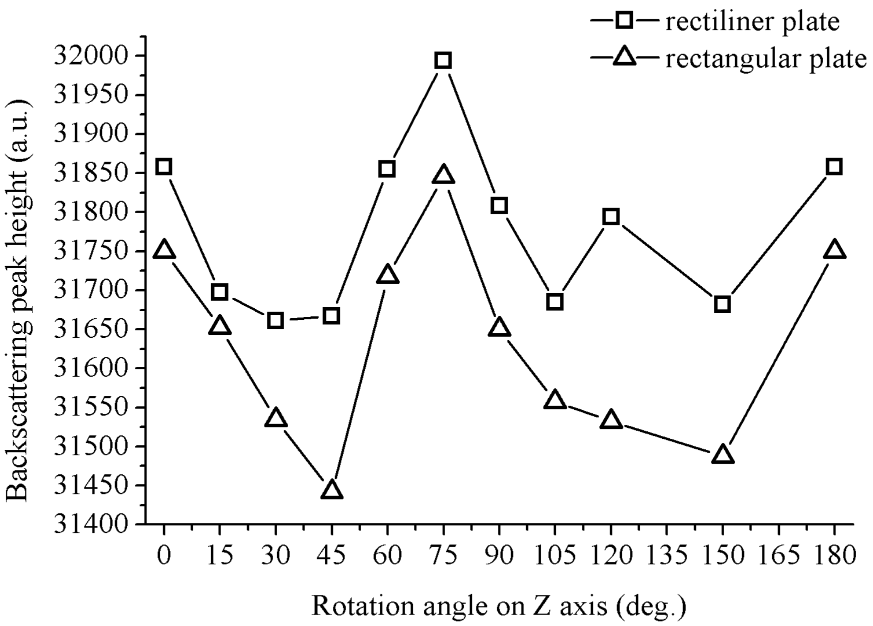


Fig. 12. Heights of the ^{137}Cs gamma backscattering peaks with different rotations of the slit on the Z-axis for rectilinear and rectangular plates.

According to the areas of the backscattering peak and the fitted polynomial curves, the effect of slit rotation on the Z-axis corresponded to a specific pattern, as shown in Fig. 13. The effect of changing the orientation was also determined for the rectilinear plate with the same thickness and volume as the rectangular plate, and with the same slit dimensions. According to polynomial interpolation, the effect can be described by the following equation: $Y_{Z\_RECTI} = 1.5E\text{-}10x^6 - 4.4E\text{-}08x^5 - 2.5E\text{-}06x^4 + 0.019x^3 - 0.187x^2 + 5.499x + 1478$.

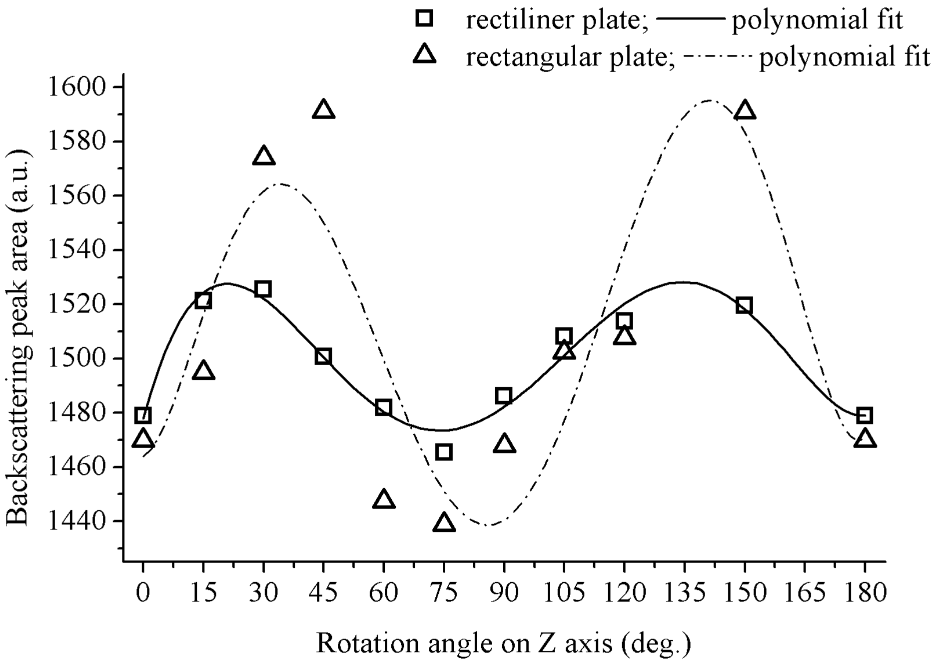


Fig. 13. Areas of the ^{137}Cs backscattering peaks with different rotations of the slit on the Z-axis for rectilinear and rectangular plates.

The backscattering peak area results obtained with the rectilinear plate exhibited a similar pattern to those produced using the rectangular plate. The only difference was that the height of the backscattering peak area curve obtained for the rectangular plate was higher than that for the rectilinear plate. According to the coefficient of determination (R^2) values for the fitted polynomial curves comprising 0.953 for the rectilinear plate and 0.753 for the rectangular plate as well as the patterns formed, we can conclude that the orientation and rotation of the slit affected the area of the backscattering curve in the energy distribution for the gamma scattering spectrum obtained with the ^{137}Cs source.

5. Conclusions

In this study, we conducted simulations to investigate the effects of the presence of different slit types and their orientation on the backscattered peak curve obtained with a ^{137}Cs gamma source. The shape of the slit had a small effect on the peak of the backscattering curve. In addition, rotation of the slit changed the peak heights and specific patterns were generated in the backscattering peak area curve.

Acknowledgment

The authors are grateful to Mataram University for support through BLU (PNBP) research funding.

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Table 1. Gaussian fit analyses of three types of duralumin (aluminum alloy) plate.

Plate type	Entries (photons detected)	Parameter	Value	Error
Rectangular block	2970440	Height	3.24488×10^{4}	1.79301×10^{2}
		Energy	1.92905×10^{-1}	1.87862×10^{-4}
		Sigma	1.49877×10^{-2}	9.24312×10^{-4}
Rectilinear block	2970607	Height	3.21878×10^{4}	1.79082×10^{2}
		Energy	1.92750×10^{-1}	2.15362×10^{-4}
		Sigma	1.62202×10^{-2}	1.17440×10^{-4}
Disk	2969772	Height	3.22524×10^{4}	1.25248×10^{2}
		Energy	1.93734×10^{-1}	1.36750×10^{-4}
		Sigma	1.84014×10^{-2}	3.88890×10^{-4}

Table 2. Gaussian fit analyses of duralumin (aluminum alloy) plate without a slit and with certain types of slit.

Plate	Entries (photons detected)	Parameter	Value	Error
Duralumin plate without a slit (8.0 cm × 6.0 cm × 1.0 cm)	2970440	Height	3.24488×10^{4}	1.79301×10^{2}
		Energy	1.92905×10^{-1}	1.87862×10^{-4}
		Sigma	1.49877×10^{-2}	9.24312×10^{-4}
Duralumin plate with a rectangular slit (0.6 cm × 6.0 cm × 0.5 cm)	2966160	Height	3.19502×10^{4}	1.31383×10^{2}
		Energy	1.92952×10^{-1}	2.23163×10^{-4}
		Sigma	1.62426×10^{-2}	4.98395×10^{-4}
Duralumin plate with a triangular slit (1.2 cm × 6.0 cm × 0.5 cm)	2966302	Height	3.15042×10^{4}	1.04053×10^{2}
		Energy	1.94316×10^{-1}	1.03424×10^{-4}
		Sigma	2.01446×10^{-2}	2.21284×10^{-4}
Duralumin plate with a semicircular slit (radius = 0.437 cm; height = 6.0 cm)	2965817	Height	3.15932×10^{4}	1.23661×10^{2}
		Energy	1.93868×10^{-1}	1.47184×10^{-4}
		Sigma	1.88921×10^{-2}	4.24362×10^{-4}

Table 3. Chi-square analysis of the backscattering peaks obtained with three types of slits.

Energy Range	Histogram height				$\left(f_{ij} - E_{ij}\right)^2 / E_{ij}$			
	Rectangular slit	Triangular slit	Semicircular slit	Σ	Rectangular slit	Triangular slit	Semicircular slit	Σ
0.180–0.185	25993.6	26234.9	26334.7	78563.2	1.0614	0.0284	0.7412	1.831
0.185–0.190	30206.7	30465.9	29904	90576.6	0.0708	2.0816	2.9206	5.073
0.190–0.195	31949.4	31561.8	31607.8	95119.0	2.4114	0.8958	0.3662	3.6734
0.195–0.200	30723.5	30832.6	30854.4	92410.5	0.0738	0.0011	0.0571	0.132

0.200–0.205	28297	28378.6	28537	85212.6	0.211	0.0782	0.5458	0.835
0.205–0.210	25902.8	25912.6	26067.5	77882.9	0.0368	0.1783	0.3772	0.5923
Σ	173073	173386.4	173305.4	519764.8	Chi-square (χ^2) value			12.137

Conflict of Interest

We declare that we do not have conflict interest of our paper with the title:

Gamma backscattering analysis of flaw types and orientation based on Monte Carlo GEANT4 simulation

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This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.

Sincerely,

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Richard Hugtenburg (Applied Radiation and Isotopes) <EviseSupport@elsevier.com> Wed, Oct 2, 2019 at 11:34 PM
Reply-To: r.p.hugtenburg@swansea.ac.uk
To: rwirawan@unram.ac.id

Ref: ARI_2018_907_R3
Title: Gamma backscattering analysis of flaw types and orientation based on Monte Carlo GEANT4 simulations
Journal: Applied Radiation and Isotopes

Dear Dr. Wirawan,

I am pleased to inform you that your paper has been accepted for publication. My own comments as well as any reviewer comments are appended to the end of this letter.

Your accepted manuscript will now be transferred to our production department. We will create a proof which you will be asked to check. You can read more about this here. Meanwhile, you will be asked to complete a number of online forms required for publication. If we need additional information from you during the production process, we will contact.

Thank you for submitting your work to Applied Radiation and Isotopes. We hope you consider us again for future submissions.

Kind regards,

Richard Hugtenburg
Editor-in-Chief
Applied Radiation and Isotopes

Comments from the editors and reviewers:

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